ANALYTICAL PERFORMANCE STUDY OF SUCTION PILES IN SAND

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ABSTRACT

Using a three dimensional finite element method of analysis, an analytical feasibility study on suction piles was conducted. Elasto-perfectly plastic soil properties were used to evaluate the effect of various cross-sectional shapes on the overall performance. Results of soil stresses and pile displacements under vertical, horizontal, and inclined loads were evaluated and compared.

KEY WORDS: suction pile, suction pressure, mobilized friction, finite element analysis, plastic properties.

INTRODUCTION

The US Navy is currently conducting a technical feasibility study pertaining to the construction of Mobile Offshore Bases (MOBs). This is expected to be a self-propelled, floating military base with a runway on top and other supporting facilities below such as living quarters, material storage areas, docking facilities for transport ships, etc. The proposed dimension of the MOB is approximately 1,500 meters by 150 meters. It is intended to be a forward-deployed, self-contained military base floating in deep waters.

The South Dakota School of Mines and Technology is participating in this MOB feasibility study to provide an adequate mooring technique for this very large floating structure. The MOBs are expected to be controlled by dynamic positioning. However, during storage, repair, or lay-up periods, or for hybrid mooring, conventional mooring techniques may be needed. Suction piles are currently being investigated analytically and experimentally to provide the necessary mooring capacity.

Suction piles typically have a large diameter (up to 30 meters to date) with a relatively small length-to-diameter ratio. They are installed by applying a suction pressure inside the pile, which acts as an external surcharge to push the pile into the seafloor. They may be retrieved later by applying a positive pressure inside the pile.

This paper describes the results of an analytical performance study on suction piles, using a three-dimensional finite element method of analysis. Three cross-sectional shapes that were thought to be able to provide adequate bearing resistance against various external loads were selected. They include circular, Y-shaped, and triangular cross-sections. These suction pile cross-sections were analyzed using the extended Drucker-Prager plasticity constitutive model to represent the complex behavior of the seafloor soil for detailed comparisons of their relative responses. Results of the plastic analysis, including the pile displacements and soil stresses, were compared in detail to identify the effectiveness of various suction pile cross-sections. The results of this study have been used in planning the laboratory model tests on suction piles.

DESCRIPTION OF ANALYSIS

ABAQUS version 5.7 (1997), a comprehensive three-dimensional finite element method of analysis software written by Hibbit, Karlsson & Sorensen, Inc., was utilized for the finite element analysis. Additionally, FEAMAP software (1986 - 1996), written by Enterprise Software Products, Inc., was used for the easy performance of pre- and post-processing of input and output such as three-dimensional mesh generation, graphical output, etc.

Model Development

The detailed dimensions of the selected piles were determined based on the same soil-pile contact area to keep the amount of the pile material the same. In addition, the length of the pile was chosen as 9.14 meters, and a cylindrical pile 9.14 meters in diameter was selected as the control. The selected cross-sections were extended into three-dimensional columns to simulate the suction piles of constant cross-sections. The cylindrical outer surface of the pile was modeled by shell elements.

Material Properties

It was assumed that the soil was homogeneous and isotropic. The behavior of the sand was characterized with elasto-perfectly plastic material properties. The extended Drucker-Prager plasticity model (Drucker and Prager, 1952) was utilized to simulate the plastic behaviors of the sand under relatively larger loads. The following seafloor sandy soil properties were used for the analysis, with the plasticity parameters reported by Shugar (1997).

Buoyant Unit Weight (γ_b) = 7.48 kN/m^3
Friction Angle (ϕ) = 26.0^o
Young's Modulus (E) = 41.73 MPa
Poisson's Ratio (υ) = 0.3

Slope Angle (β) = 46.2^o
Angle of Dilation (ψ) = 21.5^o
Yield Stress in Compression (σ_{yc})= 96.53 kPa

AISI 4340 steel was chosen for the pile material. The pile was modeled by linear elastic properties, i.e., Young's modulus (E) of 200 GPa and Poisson's ratio (ν) of 0.32. In the analysis, however, the pile stiffness was assumed to be very large so that the pile deformations did not affect the soil deformations.

Cross-Sectional Shapes

Three cross-sectional shapes studied include circle, Y-shape, and triangle. The triangular section had three equal sides. Y-shaped cross-section had three branches spaced at 120 degrees apart with identically-shaped branches. Each branch consisted of a square, i.e., the width and height were the same.

RESULTS OF ELASTO-PLASTIC ANALYSIS

The main objective of this study is to identify the most efficient suction pile cross-sectional shape through quantitative comparisons of the responses of the selected suction pile cross-sections with elasto-perfectly plastic soil properties under different loading conditions. The loads were applied along the horizontal direction, vertical direction in tension, and direction inclined at 45 degrees to the horizontal. All loads were applied at the center of the pile cap.

The initial linear elastic behavior of the sandy soil was described by Young's modulus (E) and Poisson's ration (υ), whereas the subsequent plastic behavior was modeled by the extended Drucker-Prager plasticity model. In the extended Drucker-Prager plasticity model, yielding of the material is described differently in tension and compression. In general, relatively smaller resistance against tension than compression is allowed, i.e., the kinematic hardening plastic behavior.

The load was increased incrementally and the behavior of the suction pile was observed in detail at various load levels for the different loading directions until the solutions, such as displacements, soil stresses, etc., failed to converge.

Behaviors of Suction Piles under Horizontal Loads

1) Pile Displacements

Figure 1 shows the variation of the maximum horizontal pile displacement under various horizontal loads with different pile cross-sections. The maximum horizontal pile displacement represents the maximum pile displacement at any point within the pile along the loading direction. The maximum horizontal pile displacement always occurred at the top of the pile along the loading direction, whereas the minimum pile displacement occurred at the bottom of the pile. The pile was experiencing horizontal translational movements as well as rotational movements.

As shown in Figure 1, the displacements varied linearly due to the elastic behavior under relatively small loads. As the load increased, the displacements showed a nonlinear behavior due to the inclusion of the plastic soil behavior. The variations of the curves are more or less hyperbolic shaped and, hence, it is expected that the horizontal loads will eventually approach the ultimate values. However, the ultimate horizontal load could not be obtained due to the non-convergence problem. It was found later that the solutions could be extended further by allowing the global system stiffness matrix to be unsymmetric (Bang and Cho, 1998).

As can be seen from Figure 1, the circular cross-section generated the smallest displacements at all loads. The largest displacements were always generated with the triangular cross-section at any given load. The differences in displacements among different cross-sections

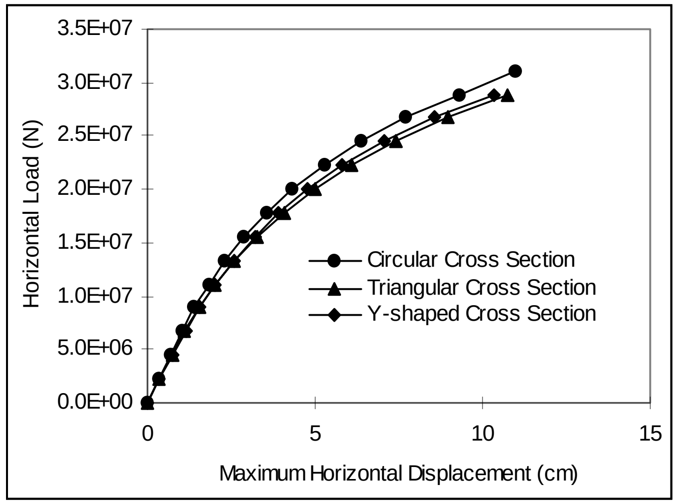

Figure 1. Maximum Horizontal Pile Displacement vs. Horizontal Load

increased with the increase in horizontal load, i.e., the effect of the cross-sectional shape is pronounced at larger horizontal loads due to the effect of plasticity.

2) Minimum Soil Minor Principal Stresses

The minimum soil minor principal stress describes the absolute maximum soil compressive stress. Yielding of the soil starts within the highly stressed element when the largest principal stress within that element reaches the yield stress (Ugural and Fenster, 1995).

The minimum soil minor principal stress at any given horizontal load was always generated at the top of the advancing side of the pile after the geostatic stress was overcome. On the other hand, as the horizontal load increased, the receding side of the pile experienced relatively small tensile stresses due to the nature of kinematic hardening in the plastic analysis.

Figure 2 shows the relationship between the minimum soil minor principal stress and the applied horizontal load. Almost identical stresses were observed for the different cross-sections under relatively small horizontal loads because the stresses generated by the applied load were not large enough. However, once the geostatic stresses were overcome, the minimum soil minor principal stresses increased nonlinearly with the increase in horizontal load. The rate of the stress increase increased with the increase in load. The effect of the cross-section became more significant at higher horizontal loads.

When the horizontal load was less than 8.9 x 10^6 N, the triangular cross-section experienced the smallest minimum soil minor principal stress, while the circular cross-section was the most effective for load magnitudes above 13.3 x 10^6 N. However, the differences in stress magnitudes among three cross-sections at horizontal loads below 8.9 x 10^6 N are very small, indicating that the circular cross-section is in general most effective in terms of the soil stress under horizontal loads.

Behaviors of Suction Piles under Vertical Tension Loads

1) Maximum Pile Vertical Displacements

The maximum pile vertical displacement obtained from the finite element analysis was approximately the same as the maximum soil vertical displacement because the stiffness of the pile was assumed to be very large. With relatively large stiffness, the suction pile moved along the direction parallel to the loading direction with almost no relative deformation of the pile.

Figure 3 shows the distribution of the pile vertical displacements for the selected cross-sections at different vertical loads applied at the center of the pile top. The relationship between the maximum vertical

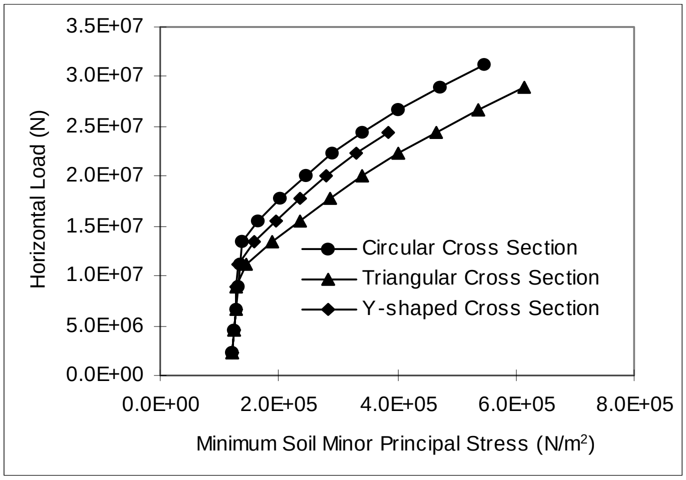

Figure 2. Minimum Soil Minor Principal Stress vs. Horizontal Load

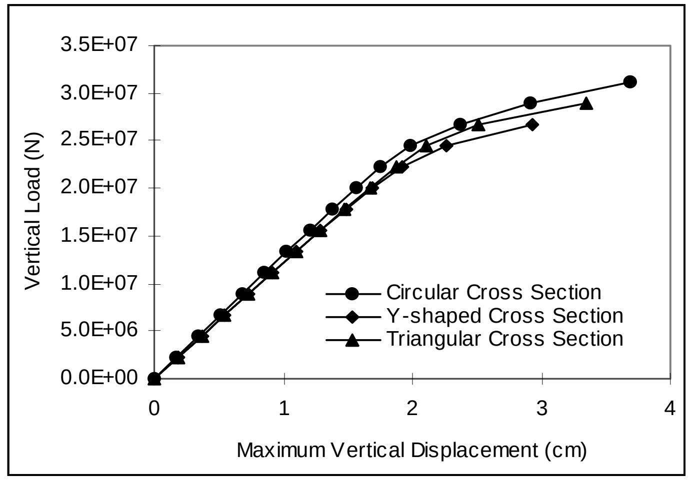

Figure 3. Maximum Vertical Displacement vs. Vertical Load

displacement and the vertical load shows the typical elasto-plastic behavior, i.e., a linear behavior at relatively low loads, followed by a nonlinear behavior due to the effect of the soil plasticity at relatively high loads. The smallest maximum vertical displacement at a given load was obtained with the circular cross-section, similar to the study results of suction piles under horizontal loads. The differences in displacements due to different cross-sections at the same vertical load increased with the increase in load. The maximum vertical displacements associated with the triangular and Y-shaped cross-sections were almost the same at relatively low loads. The elastic limit was observed at the displacement of approximately 1.83 centimeters for all cross-sections.

The vertical loads corresponding to the yield displacement of 1.83 centimeters were approximately 22.9 x 10^6 N for the circular, 22.9 x 10^6 21.3 x 10^6 N for the triangular, and 21.8 x 10^6 N for Y-the shaped cross-section, indicating that the circular cross-section is 7.7% and 5.3% more effective than the triangular and Y-shaped cross-sections, respectively

2) Minimum Soil Minor Principal Stresses

The relationship between the minimum soil minor principal stress and the vertical load is shown in Figure 4. Before the developed stresses within the soil overcame the geostatic stresses, almost identical soil stresses were observed for all cross-sections studied. However, once the soil started to yield, the minimum soil minor principal stress increased rapidly. Circular and triangular cross-sections were equally effective in terms of the minimum soil minor principal stress against the vertical loads.

Behaviors of Suction Piles under 45-Degree Inclined Loads

1) Maximum Pile Displacements

The largest horizontal displacement of the pile was always observed at the top of the pile, whereas the smallest horizontal displacement of the pile occurred at the bottom of the pile. As expected, the pile experienced translational as well as rotational movements.

Figure 5 shows the distribution of the pile displacements for the selected cross-sections at different inclined loads applied at the center of the pile top. As the load increased, the displacements gradually approached the limiting values. The increase was linear at lower loads, followed by a nonlinear behavior at higher loads. The smallest vertical displacement at a given load was obtained with the circular cross-section, as was the case with horizontal loads. The differences in displacements with different cross-sections at the same load increased
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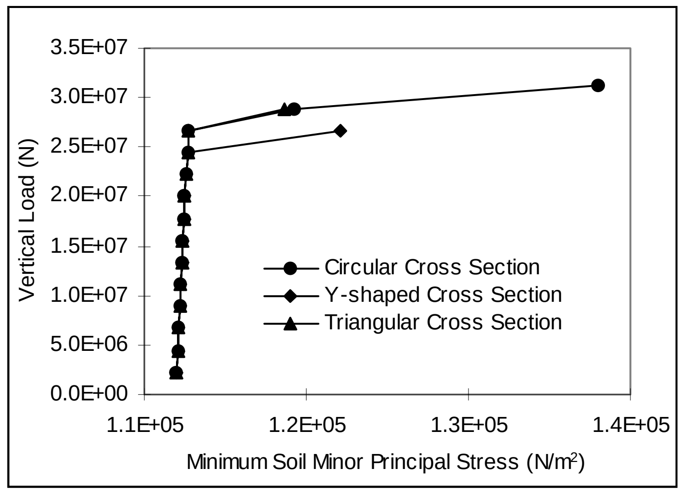

Figure 4. Minimum Soil Minor Principal Stress vs. Vertical Load

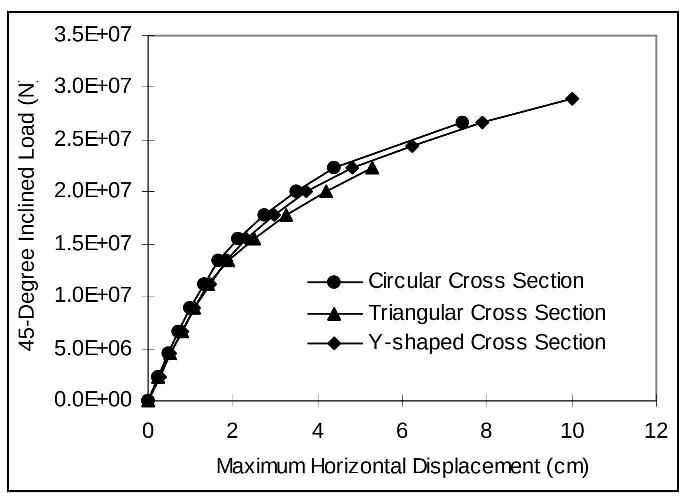

Figure 5. Maximum Horizontal Displacement vs. 45-Degree Inclined Load

with the increase in load.

2) Minimum Soil Minor Principal Stresses

The relationship between the minimum soil minor principal stress and the 45-degree inclined load is shown in Figure 6. With the increase in load, an elastic behavior followed by the plastic behavior was observed. The smallest minimum soil minor principal stress at a given load was observed with the circular cross-section. Therefore the circular cross-section is considered the most effective in terms of the soil stress under 45- degree inclined loads.

CONCLUSIONS

From the results of the finite element analyses with elasto-plastic soil properties, it is evident that the effect of the soil plasticity is significant for large load magnitudes. There also exist general trends in terms of the overall responses of the pile under different applied loads. In general, the horizontal pile displacements due to the horizontal or 45-degree inclined loads applied at the center of the pile cap vary almost linearly under very low loads but become nonlinear under high loads for all selected cross-sections. The variation is more or less hyperbolic shaped and approaches to an ultimate load. On the other hand, the vertical pile displacement due to the vertical load applied at the center of the pile cap exhibits a sudden yielding behavior at the displacement of approximately 1.83 centimeters for all cross-sections. The smallest displacement occurs always with the circular cross-section.

The observed elastic limit of 1.83 centimeters under vertical loads agrees very well with the model test results by Iskander et. al (1993). The vertical load corresponding to the yield displacement of 1.83 centimeters is the highest with the circular cross-section and the lowest with the Y-shaped cross-section.

The minimum soil minor principal stresses due to the horizontal or 45-degree inclined load applied at the center of the pile cap are dominated by the geostatic stress condition under low magnitude loads. However, as the geostatic stresses are gradually overcome, the minimum soil minor principal stresses develop at the top of the advancing side of the pile. The minimum soil minor principal stresses due to the vertical loads applied at the center of the pile cap are observed within the lower half of the pile. The smallest minimum soil minor principal stress is observed with the circular cross-section.

The vertical pile resistance embedded in sand is much smaller than the lateral resistance. Typically the pile resistance decreases in the order of horizontal, inclined, and vertical loads. This observation, however, has been obtained from the static finite element analysis of suction piles with the diameter to length ratio of 1:1. It is well understood that the vertical pile resistance increases significantly under an undrained condition when the vertical load is applied very rapidly due to the development of the negative pore water pressure underneath the pile. This phenomenon has not been studied in detail to date, but is thought to be a function of the soil permeability and the rate of load application. Therefore, a systematic study, including extensive laboratory tests, needs to be conducted to characterize the development of the negative pore water pressure underneath the suction pile before an increase in the vertical capacity of suction piles due to the negative pore water pressure can be included with confidence in the design.

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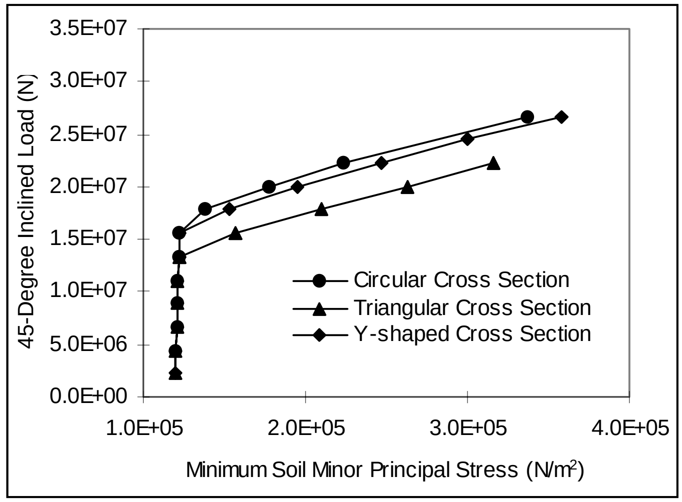

Figure 6. Minimum Soil Minor Principal Stress vs. 45-Degree Inclined Load

REFERENCES

ABAQUS/Theory Manual (1997). Version 5.7, Ch. 4, Hibbitt, Karlsson & Sorensen Inc., USA.

Bang S. and Y. Cho (1998). "Use of Suction Piles for Mooring of Mobile Offshore Bases – Performance Study." Task Completion Report submitted to Naval Facilities Engineering Service Center.

Drucker, D. C., and W. Prager (1952). "Soil Mechanics and Plastic Analysis or Limit Design," Quarterly of Applied Mathematics, Vol. 10, pp. 157-165.

FEAMAP/User's Manual (1986-1996), Version 4.5, Enterprise Software Products, Inc., Exton, PA, USA

Iskander M. G., R. E. Olsen, and R. W. Pavlicek (1993). "Behavior of Suction Piles in Sand", (ASCE) Design and Performance of Deep Foundations: Piles and Piers in Soil and Soft Rock, Geotechnical Special Publication No. 38, (eds Nelson, Smith, and Clukey), pp. 157-171.

Shugar T. A. (1997). "Numerical Modeling of Steady-State Plow/Soil Interaction", Technical Report TR-2081-SHR, Naval Facilities Engineering Service Center, August.

Ugural A.C. and S. K. Fenster (1995). *Advanced Strength and Applied Elasticity*, Third Edition, Ch. 4, Prentice-Hall, Inc., New Jersey.